Root Growth
in Connecticut Tobacco Soils

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An Introduction to
Studies made at the
Tobacco Laboratory,
Windsor

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Contents

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I. Introduction

A knowledge of the root habits of crop plants aids in their management (10, 41). The tobacco plant merits special attention, because its roots are particularly susceptible to poor soil tilth and aeration (13, 21, 36). The root systems of three types of cigar tobacco are being studied under field conditions at the Experimental Farm of the Tobacco Laboratory in Windsor, Connecticut. Observations are made on the depth, distribution, branching, and color or quality of roots to reveal the direct response of the plants to certain physical and chemical conditions of the soil profile. The studies are basic to investigations on tillage, fertilization, and irrigation and may be of value in weed control, entomology, plant pathology, and breeding (25, 41).

Methods of sampling root systems have been devised to study the relationships of roots and soil, and to measure root production quantitatively at various soil levels (3, 10, 11, 25, 27, 38, 41, 43). Pavlychenko (25) reviewed most methods used prior to 1937 and described his soil-block washing method for quantitative root studies. However, every method has its shortcomings and any one of several modifications may best meet the objectives of the investigation to be undertaken.

The following methods have been helpful in studying the root systems of plants in the coarse to medium textured tobacco soils in the Connecticut Valley. A thorough study of root systems extricated from their natural environment may at first be slow and cumbersome, but gives information not gained in any other way.

In many situations morphological reactions of the roots show soil condition defects otherwise almost undetectable. When observed under different defined soil conditions, these root indications help to establish the critical limits of the various physical and chemical soil factors for the plant under investigation.

For the correlation of root distribution with soil environment, soil profile descriptions are made as outlined in the Soil Survey Manual (30). This description characterizes the color, texture, structure, and consistency of the soils in the different horizons or subdivisions thereof. Morgan's soil test (22) is used to estimate fertility of the different soil horizons; the glass electrode to determine the pH of a soil paste. Various physical soil properties are measured in the laboratory on undisturbed soil core samples of measured volume at field moisture. More often, however, a more rapid field diagnosis of soil structure as related to root development is made by eye and by hand (see p. 5). Techniques and and some early results follow.

II. Materials and Methods

1. *Trench-tracing method.* This method, used in our first, mainly qualitative, investigations on depth and distribution of tobacco roots is similar to the trench-tracing method, using trench and sharp pointed instruments, employed extensively by Weaver (41, 42). Actually a modification of this method was used, as developed and described by Tollenaar (36). To determine the lateral spread of roots, successive trenches are dug at decreasing distance from the plant or row of plants under examination.

The so-called direct or dry methods are laborious and some finer root structures may be lost. In very stony or peaty soils, the trench-tracing method is about the only satisfactory technique (Figure 1.)

2. *Modified trench-washing method.* Another technique used in our earlier tobacco root studies could be called a modified trench-washing method, a combination of the procedure followed by Schubart and the principal feature of Kings' soil-prism washing method. The latter methods are described briefly by Pavlychenko (25).

A trench is dug beside the plant to the greatest depth of root penetration. Needles or pieces of galvanized wire are pushed horizontally into the vertical wall alongside these plants. Best spacing of these thin rods generally will be 2 by 2 inches. For root systems with a predominantly lateral spread near the surface, the horizontal spacing can be 3 inches (Figure 2).

Water under pressure is sprayed against the vertical wall to wash soil away from the root systems. The needles or wires hold the roots in position even when washing with a strong stream from a big spray nozzle. The washing, however, should be done with the greatest possible care to save the fine rootlets and avoid tangling the roots.

An adequate supply of water under pressure is essential (38). In some soils a pump may be needed to remove water and mud from the trench. In most tobacco soils comprising the flat "outwash" terraces in the Connecticut Valley, the natural drainage takes care of this wash water.

This method can be quite useful for very gravelly and stony soils.

3. *Pin-board method.* The needle or pin-board method is now almost exclusively used for intensive studies of soil-root relations at this Station. By this method a sample representative of an entire root system—a monolith of soil from the surface to the desired depth—is taken without disturbing the natural position of roots within the soil sample. In the laboratory, the root distribution is examined in detail in relation to the various horizons of the soil profile.

Needles positioned in a board hold the main roots and laterals in place while the soil is removed by soaking and washing. Thus this gives the original root distribution. Because the washing is done in a big tank of water, it is possible to see the finer details of the root systems and their relationships to soil characteristics.

According to Pavlychenko (25) this so-called nail and needle-brush washing method was introduced in 1909 by Rotmistroff and employed in his studies of plant roots grown in wooden boxes. Maschhaupt (23) was the first to use a modification of this method successfully for studies of the roots of crops grown in the field.

The pin-board technique used at the Station's Tobacco Laboratory is here described in detail.

Site Selection and Preparation

A trench or profile pit, about 3 feet wide and 4 feet long, is dug with one face 6 inches from the stems of the plants to be sampled. The depth of the pit, determined by the length of the roots, is usually not more than 18 to 30 inches in the Connecticut tobacco soils.

Soil profile characteristics are observed while a representative field location is selected and the profile pit is dug. We pay particular attention to the field diagnosis of the surface tilth and structure of the different soil horizons and their effect on root development.

As an aid in site selection, the so-called "Spatendiagnose" developed by Görbing (18) and Sekera (38) gives a useful measure of compaction in the various horizons. An undisturbed slice of soil 10 to 18 inches deep is taken with a spade. This sample is gently shattered by tapping on the handle of the spade or the soil sample itself or by "opening up" the soil by hand. With this technique the structure of the soil can be evaluated and the slightest compaction can be easily spotted in coarse to medium textured soils (Figures 3a and 3b).

Root development can be observed at the same time (Figures 4a and 4b). Important and striking root disturbances can be found with this simple spade method.

Another structural evaluation is made while studying and describing the soil profile. By lightly raking over the soil profile horizontally with a wire-toothed comb or small rake, the degree of compactness of the different soil layers or horizons becomes apparent. With repeated raking the more compacted horizons protrude from the profile. At the same time by opening up the profile the development and distribution of the roots in the various horizons will show up better (Figure 5).

Special attention can be given to the details of root distribution in relation to physical resistance, porosity, and other differences in the soil profile. Samples of the root systems and of the various soil horizons are later examined in the laboratory.

Excavating the Monolith

After these studies the soil profile is sliced off and again smoothed at exactly the desired distance from the stems of the plants, usually half the thickness of the soil monolith to be taken. We cut the slice free 1 inch in front of the 5-inch long needles of the pin-boards, thus making a 6-inch thick monolith. This size is particularly suited to tobacco; a thinner monolith would suffice for a denser root system such as grass.

The pin-board is driven against the soil profile, so that the pins are among the roots beneath the particular plant or row of plants.

The pins on our first board were made of thin, copper-coated welding rods, about ⅛ inch in diameter. Although these rather flexible pins stood up well under intensive use, later boards were provided with steel knitting needles. These needles are much thinner, more springy, probably stronger, and easier to insert into a soil profile. The board consists of 2 sheets of plywood, one ¾ inch and one ¼ inch in thickness. The ¾-inch plywood is drilled, 2 inches apart each way, so needles

can be inserted. The needles are cut to length, sharpened at the cut end, and bent into a "U" shape. The "U's" are pushed through the holes in the ¾-inch thick plywood and backed up by the ¼-inch thick plywood. Brass screws hold the boards together and thus secure the needles. Plastic putty along the edge between the boards keeps out moisture. Finally the pin-board is painted dull black to provide a contrasting background for photographing the washed, white to yellow root systems. The needles also are painted regularly to prevent rusting.

The dimensions of our boards are 40 x 24 inches or 38 x 20 inches because the distance between the rows of Connecticut tobacco is usually 36 to 42 inches. These boards are also used for examinations of the roots of cover crops, mainly small grains. In these studies the long side stands upright. Representative samples of the root systems of small grains or grasses can, of course, be obtained with much narrower boards and shorter needles. Weaver and Darland (43), using a long shallow wooden box, obtained a soil monolith 12 inches wide, 3 inches deep, and 3 to 5 feet in length for their studies of soil-root relationship of native grasses in various soil types. For studies on the distribution of roots and nodules of alfalfa and sweet clover, however, Fox and Lipps (11) enlarged the cross-sectional dimensions of the latter method to 5 by 10 inches.

In Connecticut's tobacco soils with textures ranging from loamy sand to silt loam, hand pressure will usually force the needles an inch or two into the profile. A carpenter's level set on the top edge of the board is a help in keeping the board level as it is inserted (Figure 6). Then a piece of board is held against the back of the pin-board and with a little sledge hammer the needles are forced entirely into the profile. For easier penetration, the soil profile is sometimes moistened either by watering or by furrow irrigation of the sampling site 1 or 2 days before digging the profile pit.

After this we first mark the boundaries of the various soil horizons and sub-zones on and along the edges of the pin-board with white thumbtacks, such as the contour of the soil surface along the board, depth of primary and secondary tillage zones, depth and thickness of plow soles or traffic soles and soil horizons. For a complete outline of the soil surface on the pin-board a white string can be used (Figure 30).

The monolith is then cut free at the bottom. A steel bottom plate is driven into the soil profile with a little sledge hammer. This plate is shaped like a 5-inch angle iron. The bottom part with the cutting edge goes under the bottom edge of the pin-board. To the underside of the plate two flat loops have been welded to hold a canvas belt (Figure 7).

This bottom plate serves to cut and support the monolith; support is especially important with very sandy and loose subsoils. The plate also makes it easier to lift or slide the monolith out of the trench, especially when the trench is narrow.

Then the inner face of the monolith is cut free. This can be done either by working inward with knives and spades from the sides (43) or by driving a steel sheet (23) or a long spade into the ground from the surface.

The steel sheet we use (Figure 7) is 4 to 6 inches higher and 6 to 8 inches wider than the needle-board; it is hammered into the soil

vertically. The sheet is 3 inches from the plants, or 6 inches from the pin-board. The bottom of the steel sheet has a cutting edge, but still a heavy sledge hammer may have to be used.

The steel sheet can be driven before or after the profile pit is dug and the pin-board inserted. In very loose soils, we put the steel sheet into the ground before the pit is dug.

If the soil is very hard or compact the steel sheet is not used. Instead we dig a narrow trench (one spade wide) 6 inches from the inserted pin-board. This is about 1 inch from the tips of the needles in the profile. Then an 18-inch tilespade, flat and sharp, is pushed down from the bottom of this slit; an inch from the tips of the needles. By shifting the position of the spade it is easy to cut off the monolith smoothly. Spade marks are visible on the pit wall in Figure 9.

Then the soil at the sides of the pin-board is cut away with a spade or trowel until the side edges of the steel sheet are uncovered.

The next step is to tilt into the pit the slice of soil between the pin-board and steel sheet, to lift it out, and to place it in a truck. If the lifting is done by hand the easiest way is to tip the needle-board onto two inclined planks set in the pit (Figure 8). The monolith then can be slid out of the pit over the planks by pulling at both ends of the canvas belt attached to the bottom plate. This back-breaking work, however, can be avoided by use of a power lift as shown in Figure 9.

Before transferring the monolith to a water tank, the profile description can be checked and completed. Horizon designations and depth marker placement are verified and marked with elastic white strings stretched over the monolith, or with thumbtacks. The soil monolith can, of course, be sliced and smoothed off close to the tips of the needles, so that its thickness is reduced to exactly the 5-inch length of the needles. For the tobacco root studies, however, we worked with a soil monolith 6 inches thick, including 1 inch beyond the needle points.

Schuurman and Goedewaagen (27) developed a technique for preserving soil profiles and their root systems simultaneously. The part of the monolith that exceeds the length of the pins (about 4 cm.) is used for the preservation of the soil profile.

Washing Away the Soil

In a large tank filled with water the monolith is submerged and soaked for a couple of hours, overnight, or a day or two if the soil is rather heavy or compacted (Figure 10). Soaking in a dispersing solution directly (3) or after thoroughly drying the whole monolith at a temperature of about 105°C. (27) might be needed to suspend fine textured soils before washing.

Then the soil is washed out of the root systems by gentle washing, mostly under water, with a big garden sprayer attached to a garden hose. As soon as the points of the needles are seen sticking out of the soil, it is possible to wash a little more vigorously without disturbing the morphological structure of the root systems. The best way to prevent any breaking off of soil clods from the monolith and therewith the loss of roots, is to have the water level in the tank ½ to 1 inch below the level of the soil body left on the board (Figure 11). During this washing, the more detailed soil-root relationships can be observed

under a shallow layer of water. This is a unique opportunity for noticing how in the presence of compact, resistant layers of soil the roots abruptly change direction, are malformed, or fail to branch.

Finally the pin-board with the stems at the top is slightly tilted and the roots washed free of any remaining soil and gravel. Further details on the technique of washing are given by Goedewaagen (15), Weaver and Darland (43), and Pavlychenko (25).

Photographing and Sectioning

The washed root systems are then photographed without removing the root system from the pin-board. Its deep black painted surface and needles contrast sufficiently with the roots of most species. The regularly spaced needles facilitate the study of the horizontal and vertical distribution of the roots.

Photographs, showing as many details as possible, are made while the pin-board is kept under a thin layer of water. The finer rootlets, floating freely, assume better their natural forms and positions, separate readily and do not adhere to the main root branches (Figure 12).

For detailed studies of the thickness and the degree of branching of the main roots or even of the smaller rootlets and their laterals at various soil levels a few characteristic roots can be selected. For close-up photographs these roots are floated in a small washing-trough with a black bottom (Figure 13).

Most of the photographing, however, is done quickly and satisfactorily outdoors with the pin-board vertical against a wall. The finer rootlets, however, are first allowed to assume their natural position by submerging the pin-board with root systems in a shallow tank of clean water. The water level is lowered slowly by siphoning, leaving the root system in its natural shape on the pin-board. Now it can be taken out of the tank without displacement of the finer root structures.

Upon completion of the photographing, the root systems are used for quantitative studies. They are sectioned in such a way that the oven-dry weight at 45° or 100°C. can be obtained for each 6-inch or foot depth and also for each of the major soil horizons.

The weight or the volume of roots is, of course, not necessarily a measure of the absorbing surface and thereby of the potential metabolic activity of the root system. However, when used in combination with photographs showing the morphological characteristics of the root system, such as distribution, density, thickness, and especially color of roots as on color photographs, a reasonable interpretation of the data in this respect is possible. On color photographs or slides the fleshy and shiny white younger portions of the tobacco root system, for example, stand out very clearly among the older, non-absorbing parts of the root system. The latter show a distinctly yellowish to brownish color due to the formation of a more corky cortex. The greater the density of these younger roots, the greater the physiological activity, as in a dense root system many finer rootlets will be found. Information as to the location and magnitude of the absorbing areas of the root system can be gained in this way.

This, then, is the "pin-board method" by which we are studying roots. A representative profile is selected and examined visually and

manually to detect any compaction layers. Next the profile and its roots are impaled on needles in order that a monolith can be cut away and removed intact to a washing tank. Here, as the soil is washed away, is an excellent opportunity for seeing how in the presence of compact, resistant layers of soil the roots abruptly change direction, are malformed, or fail to branch. Finally, with the roots held in their original position by the needles—but with the soil gone—one can photograph them and judge their activity from their appearance.

4. *Core or auger method.* Another method used for the tobacco root studies is the core or auger method, utilizing soil cores for the determinations of root concentrations. This technique is simple and relatively quick and many modifications have been used and described (6, 10, 15, 29, 40).

Simon and Eich (29) made an intensive study on the merits and reliability of the auger method as compared with those of the steel sheet sampling-box method of Köhnlein and Vetter (20). At least 10 to 12 core samples of a diameter of 12 to 20 cm. were needed for a useful mean weight of roots; the standard deviation of a single observation of the weight of roots in a core sample of that diameter is about one-fourth of the mean. In their studies of grass root weights, the variability was decreased by enlarging the cross sectional sample area, i.e. by use of an Albrecht auger with a 30 cm. diameter. The depths of sampling in these studies was from 0-35 cm.

The 2¾-inch wide sampler we used (Figure 7) was made from an old core or posthole type auger, as shown in the Soil Survey Manual (30), by removing the cutting blades and reducing the length of the barrel to about 6 inches. The handle of the auger is marked off in 6-inch increments, so that successive 6-inch soil layers can be sampled from a single sampling hole. These 6-inch core samples are subdivided with a knife along transitions between soil layers or horizons if sampling of the successive horizons is desired.

In medium to coarse textured soils this auger worked quite satisfactorily. A device as developed by Visser (39), however, would facilitate the removal of the core sample out of the cylinder (See also 15). The sampling equipment as used for determining soil bulk density by Broadfoot (5) appears even more convenient in this respect. Ward (40) used steel cylinder samples with crimped and sharpened ends to make the soil cores smaller than the cylinders for easy removal from the top of the cylinders. Simon and Eich (29) used Albrecht's (1) auger with diameters of 30, 20, 12, and 8 cm.

The soil samples of a known volume are put in paper bags and taken to the laboratory. Soaking the samples in a dispersing solution to suspend the soil particles may facilitate the separation of roots from soil (6). Several techniques for washing these root samples have been developed (6, 10, 12, 15, 37). The soil of the core samples is washed from the roots over a set of screens with 2, 1 and 0.5 or 0.25 mm. sieve openings. For the investigations of the coarse and fleshy tobacco roots, the 0.5 mm. aperture proved to be small enough to prevent any significant loss of roots.

These washed roots can be kept preserved in jars of water with a concentration of about 3 per cent formalin while they await final cleaning and examination. The root samples are then cleaned of soil

particles still sticking to the roots, and the small rootlets are separated from organic debris left from previous tobacco and cover crops as well as the numerous tobacco seed coats ubiquitous in every tobacco soil. This cleaning is a tedious and laborious task and is done mainly by screening and decantation procedures and by the use of tweezers.

After completion of detailed studies of the nature and mode of branching of the roots, the root samples are put in petri-dishes or small paper bags, oven dried and weighed.

The advantage of the auger method is that it can be used even on small experimental plots without significantly damaging the crop or disturbing the soil layers. The core samples give information about the maximum depth of root penetration, the effective rooting depth, the mode and rate of root branching and the quality of the roots. Furthermore, this method is suitable for quantitative and statistical studies of the root distributions in the various soil horizons (29). It is, however, much less convenient for relating the details of root development to soil profile characteristics, and it does not give such a complete picture of the pattern of root development as does the pin-board method. For most root studies best results may be expected from a combination of both methods (15, 37).

III. Description of the Soil

Up to the present most of our root work has been made on the experimental fields of the Tobacco Laboratory. Before its establishment in 1922, most of the area had been cropped to tobacco; for many years these fields have been under the traditional, almost continuous, tobacco plus cover cropping system (2).

The main soil types in these fields are Merrimac sandy loam and fine sandy loam, and Windsor loamy sand.

The Merrimac soils, developed in glaciofluvial terraces and plains, are widely used soils for the growing of cigar tobacco[1] in the Connecticut Valley.

Merrimac sandy loam, being one of the important tobacco soils and the predominant soil type on the Experimental Farm and our root study sites, will be described here. This soil, classified as brown podzolic, is developed from glacial outwash, principally granite, gneiss, and schist (4, 35). The texture is intermediate and characteristic of the predominantly moderately coarse-textured, well-aerated, and well-drained tobacco soils. The typical tobacco soil in the Connecticut Valley ranges in texture from a very fine sandy loam to loamy coarse sand. The extremely sandy soils, like Carver and Windsor loamy sand and loamy coarse sand, are not so suitable for open field types due to excessive droughtiness and leaching. The coarser-textured soils are used for shade-grown tobacco because they produce a lighter colored, more elastic, thinner leaf and, therefore, more desirable wrapper tobacco.

The physiography, drainage, geology, parent material, climate, natural vegetation, and some other characteristics of Merrimac soil and some

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[1]All tobacco grown in Connecticut is used for cigars (2). The shade type is grown primarily for cigar wrappers (the outer layer); Broadleaf and Havana Seed, the other two types grown, are used for cigar binders (the layer just under the wrapper).

of the other tobacco soils[2] have been presented elsewhere (24, 32). Since an extensive profile description of the Merrimac fine sandy loam, sampled at Windsor, has been published (4), only a somewhat shortened description of a cultivated sandy loam profile (Figure 14) is included here.

Soil Profile Merrimac Sandy Loam (Rye Cover Crop)

Horizon	Depth in inches	Description
A_{p1}	0 to 3½	Dark brown (10 YR 4/3-4/4)[3] sandy loam; very friable; weak medium and coarse crumb structure; filled with roots; lower boundary rather abrupt (disk-sole).
A_{p2}	3½ to 8	Ditto; friable; massive in place but when removed breaks into weak medium and coarse subangular blocks; roots common; abrupt and smooth boundary.
A_{p3}	8 to 12½	Ditto; when removed breaks into very coarse moderately weak angular blocks, which can be ruptured across natural surfaces of weakness into thick and very thick weak platy fragments; few roots; lower boundary sharp and somewhat wavy. less than 1 inch to 6 inches thick.
B_{21}	12½ to 17	Strong brown (7.5 YR 5/6-5/8) sandy loam; compact; when removed breaks into weak medium and coarse subangular blocks, which can be ruptured into thick platy fragments, however, not so easily and distinctly as in previous horizon; few roots.
B_{22}	17 to 23	Ditto; very friable; very weak medium and coarse subangular blocky; very few roots.
B_3	23 to 26	Strong brown (7.5 YR 5/6 + 5/8) loamy sand, containing small pebbles and fine gravel; loose; roots present.
D_1	26 to 36+	Light yellowish brown and lighter, dries out to grayish hue (10 YR 6/4 + 7/2); loose coarse sand with fine gravel and some small pebbles.

Table 1 records some of the physical data of this soil. The coarse sand (approx. 20 per cent), fine sand (approx. 24 per cent), and silts (approx. 23 per cent) are the main components down to the B_{22} level, but below this horizon coarser particles are more abundant. The clay content is relatively low and uniform from the A_p to B_{22} horizons (approx. 6.5 per cent); then the clay decreases (35).

The data on bulk density and porosity of this soil under tobacco cultivation show very clearly that the present plow layer ($A_{p1} + {}_2$) is underlain with an abrupt boundary by a very distinct plow sole and traffic pan. In the upper subsoil horizon the bulk density increases sharply from 1.44 to 1.65, while the non-capillary porosity decreases from 14.5 to 7.8 (see also Figures 3, 4 and 5). Bulk densities for uncultivated Merrimac soils show only a gradual and slight increase with depth, i.e. 1.134 for the 0-6 in. depth to 1.525 for the 24-30 in. depth (33).

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[2]Detailed descriptions of the soils that occur in the Connecticut Valley may be found in Soils of Hartford County, 1956, The Connecticut Agricultural Experiment Station, New Haven. Copies are available on request.

[3]Munsell color notation of moist soil.

Table 1. Physical data of Merrimac sandy loam, Tobacco Laboratory, Windsor, Connecticut

Horizon	Soil	Mechanical analysis: Sand	Silt	Clay	Bulk density	Porosity: Capillary	Non-Capillary	Total
		%	%	%	g/cc	%	%	%
A_{p1}	Plowed and cultivated	70.15	23.42	6.43	1.36	30.7	16.4	47.1
A_{p2}	Plowed	70.70	23.63	5.67	1.44	29.4	14.5	43.9
B_{21}	Upper subsoil	68.34	24.76	6.90	1.65	28.7	7.8	36.5
B_{22}	Lower subsoil	....	....	......	1.50	29.6	13.2	42.8

The part of the A_p horizon that has not been plowed recently, i.e. the compacted, platy-structured A_{p3} horizon (see the profile description on page 11) varies in thickness from 0 to 6 inches on the Station farm and was not sampled separately. This A_{p3} subdivision of the surface soil occurs quite commonly in the older soils of this tobacco area, probably because plowing was formerly deeper than in recent years. In the 1870's, for example, plowing to the depth of 12 inches (17, p. 175) or even deeper (17, p. 65) was highly recommended for the growing of tobacco or corn. This is at least 3 inches deeper than the presently, generally practiced plow depth of 7 to 9 inches.

In the Connecticut Valley these compaction pans at plow depth, induced by implement traffic, can be generally observed on land cropped to intensively cultivated crops such as tobacco, vegetables, and corn. The predominantly coarse to medium textured soils are naturally weakly structured and easily compacted under mechanized farming.

Such a compaction zone in a soil profile acts as a physical barrier to root penetration for most plant species. The effect of the high soil density or low pore space below plow depth on the rooting depth of the tobacco in Merrimac sandy loam has been shown to some extent in Figures 1, 2, 4b, 5, 12, and 13.

Figures 15 and 16 demonstrate the effect of the compaction on the root growth of Rosen rye seeded in September. The root development of rye 9½ weeks old, on a field not far away from the site of the profile shown in Figure 14, is abruptly restricted by a compact plow sole at a depth of 10 to 11 inches. The mature root systems of Rosen rye 33 weeks old, taken from the profile of Figure 14 show the ultimate ability of this plant to penetrate the compaction zone of Merrimac soils. This difference in root penetration is probably related to the length of the growing time for mature rye plants, although a slight difference in soil compactness below plow depth in the two fields could account for some of the difference between these two root profiles.

Figure 18 illustrates that oats grown as a cover crop during a relatively short fall season developed a deep and profuse root penetration in Merrimac soil which had been made relatively open and permeable throughout the profile. During the same period the root elongation of oats on an unloosened Merrimac profile was greatly restricted by a densely compacted layer just below the depth of spring plowing (Figure 19).

Photographs on the 11 pages following show the growth pattern of tobacco roots in Merrimac sandy loam under different systems of soil management. The pin-board technique and other methods of examining roots are illustrated, as are the root systems of cover crops. Other photographs show typical soil profiles and the soil structure as revealed by spade tests.

FIGURE 1. The trench-tracing technique as used to examine roots of a Havana Seed tobacco plant. Slices of soil 4 inches wide and 3 inches deep have been removed from the vertical wall of a semi-circular trench dug 6 inches from the stem base.

FIGURE 2. The 6-inch section here washed away from the soil profile dug across the tobacco row shows this pattern of the Havana Seed tobacco root system. Roots are largely confined to the upper 6 inches; the compaction pan, shown protruding, stopped root penetration. Wires thrust into the profile help to hold roots in position.

FIGURE 3a. Spade test of Merrimac sandy loam shows, from right to left: 0-4 inches, weak medium and coarse crumbs; 4-9 inches, weak medium and coarse subangular blocks; 9-13 inches, moderately weak very coarse and coarse angular blocks; 13-17 inches, weak medium and coarse subangular blocks; 17 inches and deeper, very weak medium and coarse subangular blocks. Compaction pan is at 9 to 17 inches.

FIGURE 3b. The compaction pan (9 to 17 inches) shown in Figure 3a forms a laminated layer. The blocklike clods were fractured by hand into weak platy fragments, coarse to very coarse, on surfaces of weakness.

FIGURE 4a. After-harvest spade test of Merrimac sandy loam in a Havana Seed field shows that 18-inch slice breaks into two main sections: furrow slice or plow layer at the right, compaction layer on the left. The massive-structured plow layer is capped by a crumbly to subangular blocky cultivated zone. No roots penetrated the compaction layer.

FIGURE 4b. The furrow slice and compaction pan clods shown in Figure 4a turned to show their common plane, the plow sole. Roots grew to the bottom of the plowed layer at right, then turned along the distinct top of the compacted soil at left.

FIGURE 6. The pin-board is driven into the soil profile so that the board touches the face of the trench. The bottom plate, shown in background, is driven into place before the monolith is cut free.

FIGURE 5. Merrimac sandy loam profile 6 inches from a row of harvested Havana Seed plants. The raked face of the pit shows soil compactness and root development in different horizons. 0 to 2.5 inches (A_{p11}), hilled up by cultivation, very friable, numerous smaller roots; 2.5 to 6 inches (A_{p12}), layer of secondary tillage, friable, filled with roots; 6 to 11 inches (A_{p2}), lower, uncultivated part of the plow layer, slightly firm, roots present along cracks and in pockets with buried organic material; 11 to 14 inches (A_{p3}), part of the A_p horizon not recently plowed, compact, no roots visible; 14 to 18 inches (B_{21}), upper subsoil, compact; 18 inches + (B_{22}), deeper looser subsoil, friable. Complete profile description is presented on page 11, see also Figure 29.

FIGURE 7. Root-sampling tools and equipment: when the short bottom plate is used the steel sheet is turned and an auger hole made for the pipe-rim.


FIGURES 8 and 9. Soil monolith with root sample resting on the pin-board and bottom-plate, cut free by steel sheet, ready to be slid from the pit. (Right) A monolith, inner face cut with long spade, lifted and transported by the hydraulic lift on tractor.


FIGURES 10 and 11. A soil monolith with oat plants on the pin-board rests in the washing tank as it is filled with water for soaking. During washing the taps in the tank are adjusted to lower the water level as soil is washed away.

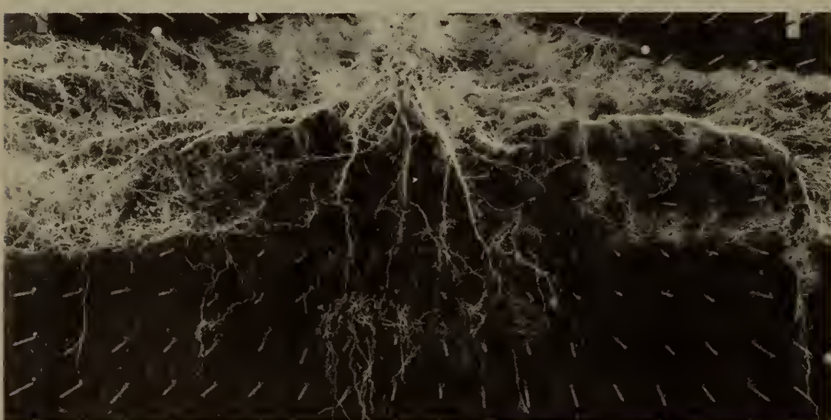


FIGURE 12. Root system of a Havana Seed tobacco plant from a monolith of Merrimac sandy loam photographed on a submerged pin-board. Few roots extend into the compaction zone (A_{p3} and B_{21} horizon) below plow depth. Most roots are in the A_{p1} horizon, the upper 6 inches, where main roots spread laterally or somewhat downward with profuse branching.

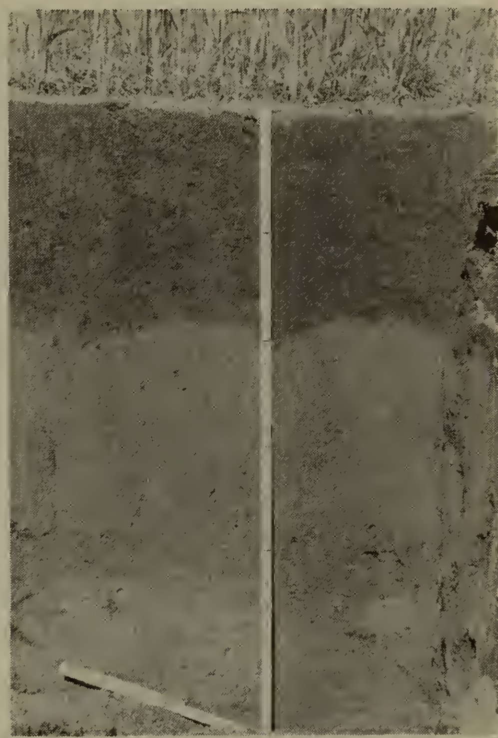


FIGURE 13. A submerged portion of a root that extended below plow depth in the system shown in Figure 12. The high soil density of the compaction pan caused profuse branching into short, mostly crooked laterals and the thickened knotted roots, formed as the root searched out the most easily penetrated area in the compacted soil. Along old root channels or worm burrows the roots grew together into twisted threads and clusters.

FIGURE 14. (Right) Profile of a cultivated Merrimac sandy loam. A detailed description is given on page 11.

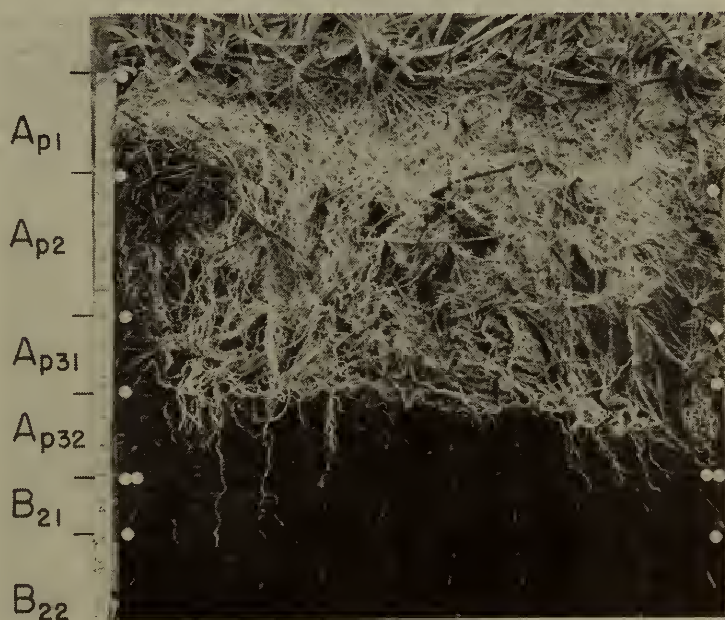


FIGURE 15. Root system of rye grown 9½ weeks in Merrimac sandy loam. A_{p1} horizon, depth of seedbed disking, is matted with roots; A_{p2}, extending to most recent plow depth, is well filled with roots; A_{p31}, an older part of the A_p horizon, shows roots still abundant but deeper penetration is blocked by plow sole at bottom; A_{p32} has few roots. B_{21} horizon is the compact upper subsoil.

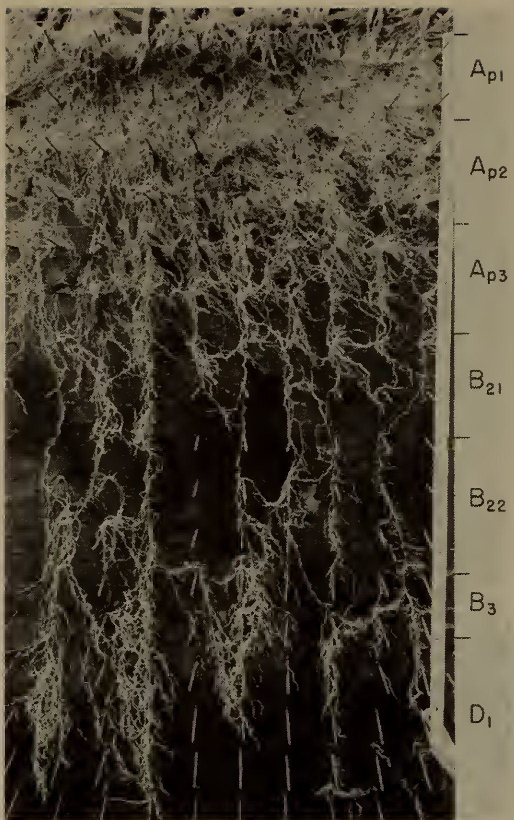
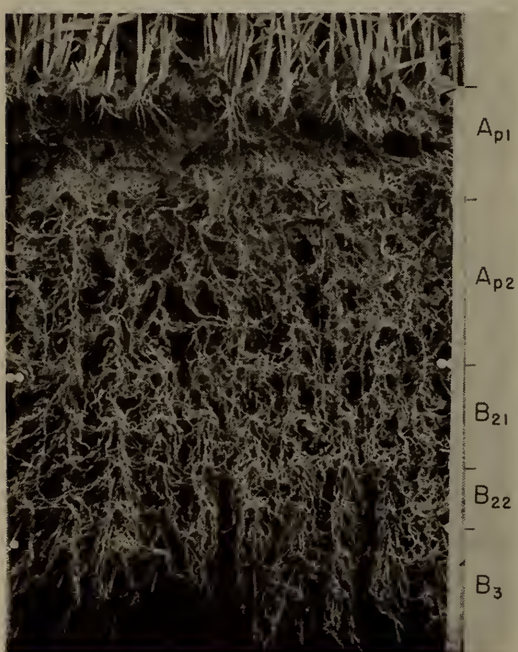


FIGURE 16. Roots of rye 33 weeks old taken from the profile shown in Figure 14 and described on page 11. Root growth is noticeably less dense in the compaction zone; roots passing through are well branched in deeper subsoil (B_3) and substratum (D_1).

FIGURE 17. (Right) This subsoiler is used to loosen compact layers below plow depth.



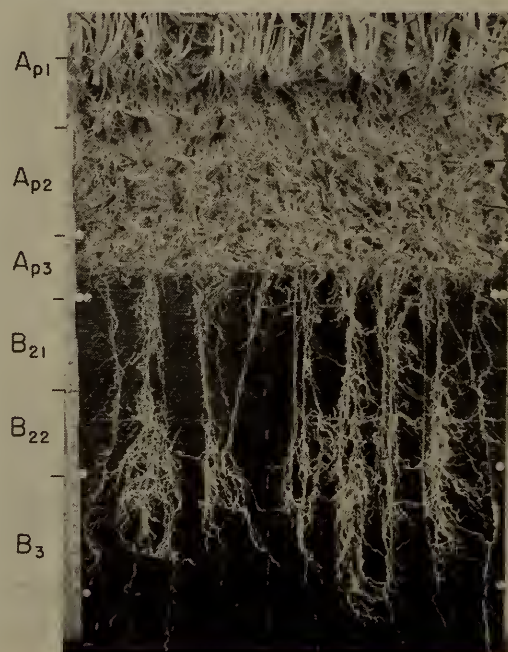


FIGURE 18. Root system of oats 11 weeks old grown in Merrimac sandy loam loosened with a fork to a depth of 20 inches with minimum mixing of different horizons. The compaction pan was loosened for the tobacco crop in May and a cover crop of oats was sowed in mid-September.

FIGURE 19. (Right) Root penetration of oats 11 weeks old is limited by older plow sole (in A_{p3}) and compacted upper subsoil (B_{21}). Root profile is from an unloosened check plot adjacent to that of Figure 18.

FIGURE 20. Profile of Merrimac sandy loam with compaction pan at about 9 or 10 inches, mainly the B_{21} horizon. Shown about 10 weeks after the soil was chiseled and then seeded with rape in early September.

FIGURE 21. Root systems of 10-week-old rape in a 5-inch monolith taken from the soil profile shown in Figure 20. White tacks at sides indicate horizon transitions at 10 and 19 inches; those at bottom mark lateral spacing of subsoiler channels in the monolith.

FIGURE 22. Roots of overwintered rape plants 8 months old taken from the plot of Figures 20 and 21. The soil has not been completely washed from the root systems, to hold the heavy plants in position.

FIGURE 23. Merrimac sandy loam profile on a harvested tobacco plot, one year after being subsoiled. Subsoiler channels at 16- to 17-inch depth between the rows are clearly defined and filled with tobacco roots.

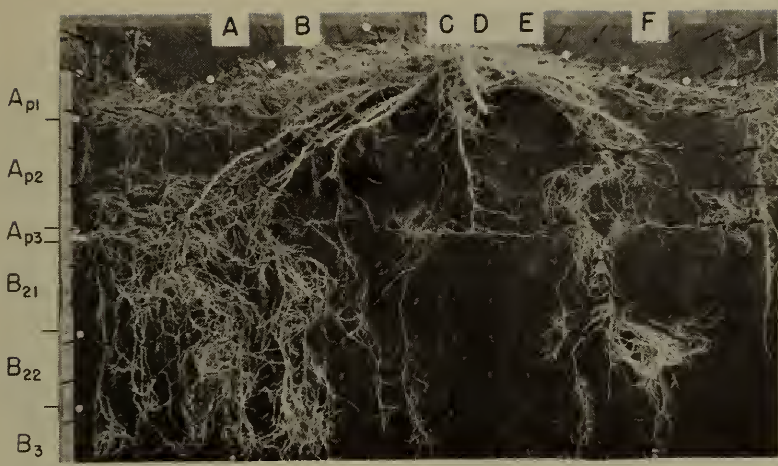


FIGURE 24. Root system of Havana Seed tobacco plant in a 6-inch monolith taken from profile shown in Figure 23.

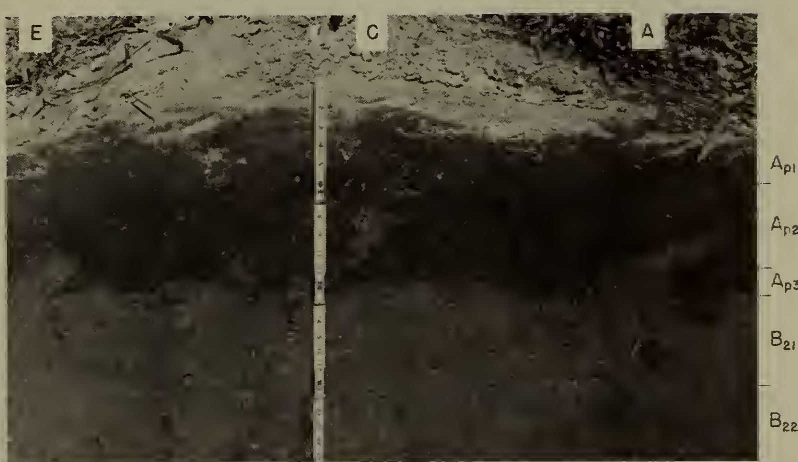
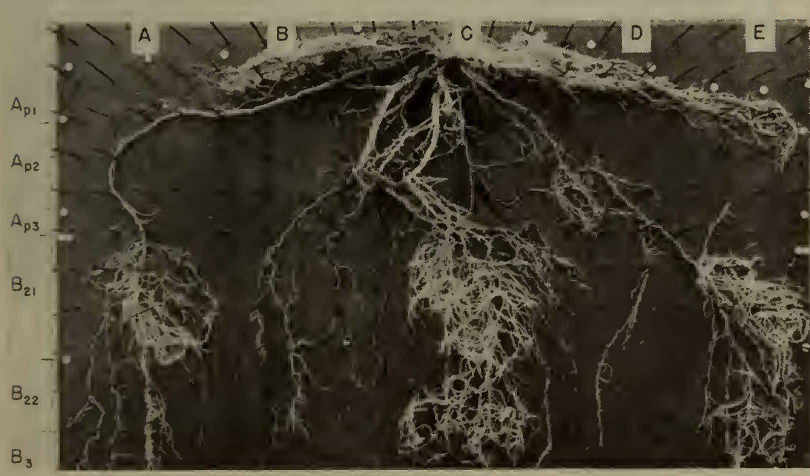
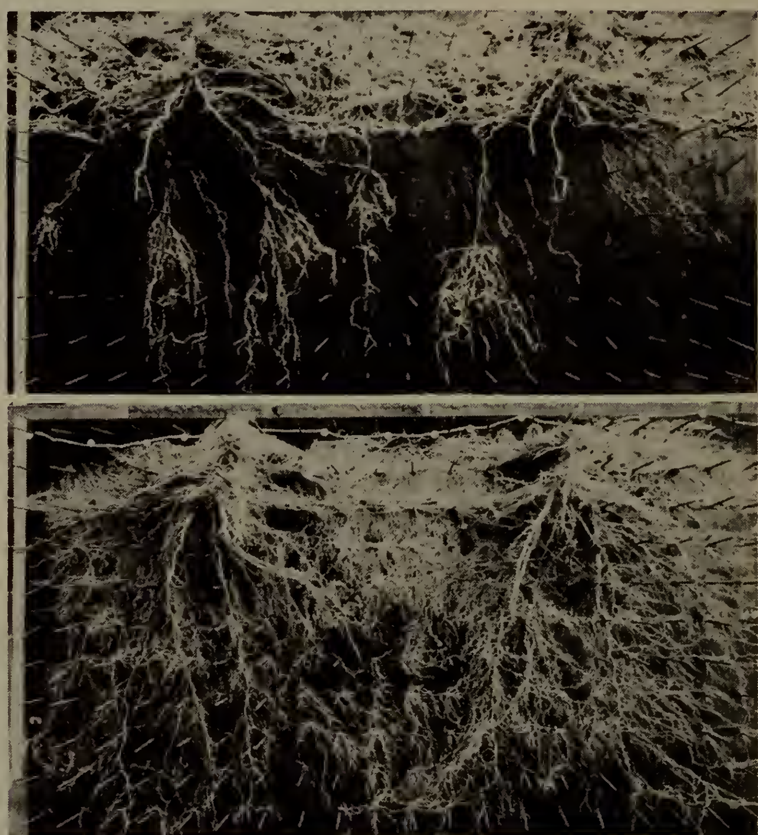


FIGURE 25. Merrimac sandy loam profile across a row of harvested tobacco. The plot was loosened and fertilized to a depth of 16 inches at the time of 8- to 9-inch spring plowing. Light-colored subsoil (B_{21} material) has been lifted into the A_p horizon. At A, C, and E the subsoiler used with a 16-inch plow left its mark in the A_{p2} and A_{p3} horizons.

FIGURE 26. Root system of a harvested Havana Seed tobacco plant, 72 days after transplanting, taken from the profile shown in Figure 25. At A, C, and E the three fractured and fertilized zones in the compaction pan are well rooted, as is the deeper subsoil.



FIGURES 27 and 28. Root systems of mature Broadleaf tobacco grown on Windsor loamy sand, fall-plowed to a depth of 14 inches. On area in top photo oats and rye cover crop was plowed under (6 to 7 inches) before fertilizing plot and transplanting tobacco. On area in lower photo no cover crop was grown. Note root stratification from recompaction by shallow plowing and secondary tillage.



FIGURES 29 and 30. Havana Seed plants from the Merrimac sandy loam profile shown in Figure 5, 8 weeks after transplanting. In top photo roots are mostly confined to the 6-inch depth of secondary tillage. Sharp boundary in root development marks area of disk-sole compaction. In lower photo plants of the same age nearby on the same soil type show well branched roots to a depth of 2 feet in an open-structured profile, loosened and managed by hand.

In the soils under discussion the mechanical resistance of the compaction pan to root penetration, due to small size of pores (Table 1), seems to be for all crops the main factor in limiting root penetration and branching.

Soil aeration is known to be affected by total pore space and size of pores in the soil. Preliminary investigations of the renewal rate for diffusion of oxygen into loosened and unloosened Merrimac soils on the Station farm, as measured by the method developed by Raney (26), did not indicate any effect of the compaction pan on soil aeration. A barely detectable decrease in renewal rate, however, was found in an excessively packed Merrimac sandy loam profile.

Textural differences cannot be given as a reason for the restricted root growth because the compaction zone in the B_{21} horizon is similar in texture to the tilled soil in the A_p horizon above it (Table 1).

Other studies (to be published) on Merrimac sandy loam showed no correlation between root depth and organic matter, soil acidity or the fertility status of the soil below plow depth. Loosening or lowering the mechanical resistance of the compaction zone in these well drained soils, without deep placement of lime and/or fertilizer, will generally promote deeper root penetration, as already shown in Figure 18.

In the present studies the effect of the deep tillage operations is measured solely by the root development and no attempt has been made to relate the achieved root distribution to food- and water-uptake by the plant and its ultimate effect on yield and quality of the crop.

IV. Examples of Root Distribution as Affected by Deep Tillage

Presently a series of field trials on deep tillage are being carried out at the Tobacco Laboratory in Windsor. The soil types used are Merrimac sandy loam and Windsor loamy sand with a compaction pan at plow sole depth, as described in the previous chapter.

Deep tillage, tillage in the zone below the normal plow layer which is undisturbed by ordinary tillage methods, can break up the compaction pan. It can be accomplished in several ways with different degrees of inversion of the soil. The loosening or shattering of the compaction pan will lower or erase its physical impedance to root penetration and thus extend the area of exploitation of plant roots for nutrients and water as already shown in Figure 18.

The root systems of most plants generally show a marked response to the soil conditions in variations in root depth, spread, branching, and quality. Therefore root growth is the first yardstick used in our investigations of the effect of different tillage and soil management practices on crop growth. Such studies on soil-root relationships with special emphasis on the details of the relation of the soil profile and physical resistance to root development "give not only a logical cause for the results obtained in crop growth and yield, but at the same time form a more scientific basis for improvement in these practices" (41). As Gliemeroth (14) puts it, the plant root is the decisive link in the chain leading from the actual soil conditions to crop yield.

Furthermore, such root pattern studies may be the best way for growers to visualize the clear and striking influence of defects in soil condition and in management practices.

Subsoiling

Loosening of compact subsurface soil or subsoil without appreciable soil inversion can be done with a subsoiler similar to the one shown in Figure 17. Such a standard subsoiler with a $2\frac{1}{2}$-inch chisel may be drawn through the soil at depths from 15 to 24 or more inches and at spacings of 18 inches or more. Ordinarily such shattering of plow and subsoil pans is carried out most effectively when the soil is quite dry. For effective shattering, subsoiling must extend through the compaction zone.

On Connecticut's intensively cultivated soils deep tillage is best done in late summer or early fall, as soon as the cash crop is harvested and just before seeding of the winter cover crop. Soil bearing strength is greatest and compaction susceptibility least at the end of the cropping season when soil moisture is depleted. The root systems of the winter cover crop, which penetrate the deeper soil layers as a result of subsoiling, will help to hold and improve the fractured condition of the compaction pan. Especially in these medium to coarse textured soils very little more permanent improvement in soil structure can be brought about by tillage operations alone.

Figure 20 shows a profile of a tobacco field on Merrimac sandy loam subsoiled with the machine pictured in Figure 17. Subsoiling was done September 9, a few weeks after the tobacco harvest, and the same day the field was disked and seeded with a crop of Dwarf Essex rape. After about 10 weeks (November 18) a profile was dug in this field perpendicular to the direction of subsoiling. The profile is raked to expose the root distribution of the rape plants and show the degree of looseness of the different soil horizons. The bottom of the subsoiler worked at a depth of about 16 inches, just below or at the lower boundary of the compaction pan. The channels are still open and spaced about 2 feet apart. The areas or trenches of loosened soil above the channels widen up to the surface and are well filled with roots. Between these trenches are dikes made up of unshattered compaction pan which block root penetration. Hardly any roots are visible in this unbroken block or dike of soil or in the deeper soil layers directly beneath it.

A 5-inch thick monolith taken with a pin-board from this soil profile, after it was again smoothed, shows more clearly the root distribution of the rape plants (Figure 21). The close relationship is apparent between this root distribution pattern and the pattern of the loosened zones of the soil profile. In fact the distribution is a very precise reflection of the loosened-zone pattern.

Figure 22 shows the root pattern of rape plants on the same plot as shown in Figures 20 and 21 after surviving a not too severe winter. Although the tops of all rape plants had been winterkilled, the presumably more vigorous plants formed new shoots after the last frost and bloomed in the following spring. Most of these plants were on or near the strips above the subsoiler channels. The root profile shown in Figure 22, sampled about 8 months after seeding (May 15), shows that more vigorous tap roots of the rape plants developed in or near the subsoiler furrows. The chisel channels were still open in the soil monolith and the lateral spacing of the channels is marked by pairs of thumbtacks at the bottom of the pin-board.

Table 2. Description of profiles and root distribution

Depth beneath hill	Soil horizon	Root weight: Oven dry	Root weight: Relative below 6″[1]	Sampling position[2]	Bulk density	Field moisture[3]	Penetrability[4]
Inches		g/100	Per cent		g/cc	Per cent	No. of strokes
		As shown in Figures 23 and 24					
0 to 6	A_{p1}	5831	...	...	...	...	....
6 to 12 or 13	A_{p2}	565	78.9	B	1.39	13.4	8½
				C	1.37	13.1	6¾
				E	1.55	12.7	10¾
12 to 13	A_{p3}	....	...	...	...	...	....
12 or 13 to 18	B_{21}	77	10.8	A	1.54	13.3	6
				D	1.67	13.3	18½
				F	1.62	13.0	10
18 to 22	B_{22}	47	6.6	...	...	...	....
22 to 25	B_3	27	3.8	...	...	...	....
		As shown in Figures 25 and 26					
0 to 5½	A_{p1}	6052	...	...	...	...	....
5½ to 10¾	A_{p2}			B	1.53	13.0	10½
		309	63.8	D	1.52	12.9	10¼
10¾ to 12	A_{p3}			...	...	...	....
12 to 18	B_{21}	117	24.2	B	1.63	16.2	14
				D	1.64	15.6	16¾
				A	1.41	15.2	4½
				C	1.39	15.4	5¼
18 to 24½+	B_{22}	58	12.0	...	...	...	....
	B_3						

[1]Layer from 0 to 6 inches is excluded because a few thick woody roots would completely overbalance the weight of the younger absorbing portion of the root system. Furthermore the deepening of the rooting zone is the main interest of this work.

[2]See appropriate figures for location. Duplicate core samples.

[3]When sampled.

[4]Number of strokes of a 12-pound hammer dropped 2 feet required to drive a 3 5/16-inch diameter core sampler 3⅜ inches into the soil (31).

Figures 23 and 24, and Table 2 show the effect of subsoiling on the root development of the following tobacco crop and give some indication of the durability of the shattered soil condition in intensively cultivated tobacco land.

The Merrimac sandy loam profile shown in Figure 23 was excavated September 6 from a harvested tobacco plot that had been subsoiled and seeded to oats the preceding fall (September 9). After spring plowing, Havana Seed type tobacco was grown according to the standard practices for this area (2).

In the upper subsoil the chisled profile shows the trenches full of loosened soil alternating with the dikes of compacted soil. This is similar to the profile shown in Figure 20. The perpendicularly transected chisel channels are easily found as they are still open and filled with clusters of shiny white tobacco roots. The trenches above these channels hold more roots than the dikes of unbroken soil. Manual examination of the soil profile with the little wire rake, however, indicates that the shattered soil layers above the channels are not as loose and well rooted as those of the profile in Figure 20, presumably due to the collapse of the soil mass. Although some consolidation may be expected from the resettling of the shattered soil layers under the influence of natural forces, the main causes of recompaction are probably tractor traffic and compacting action of implements during intensive tobacco culture (see page 33).

The root profile (Figure 24) shows first of all that root penetration was once again greatly impeded by the unbroken compaction pan between the 2 subsoiler grooves, which are marked by the cluster of roots at F and A in the B_{22} horizon. The main root lateral at C in the A_{p2} horizon grew to the bottom of the plow layer and was stopped there in its downward growth by the high density of the soil (bulk density 1.67 at D, B_{21}, see Table 2); consequently it turned sideways and followed with its laterals the top of the compaction pan.

The same rooting condition can be observed at F in the B_{21} horizon, although this area is directly above the chisel channel in B_{22} and was cut by the subsoiler beam. Compaction by the plow and the tractor rear wheel on the moist soil in the furrow bottom during spring plowing apparently repacked this particular area so that the bulk density (1.62) approaches that of the unshattered compaction pan between the subsoil furrows.

On the other hand, in the area of A, B_{21}, which is above the other chisel channel, hardly any impedance of root penetration below plow depth is indicated. From Table 2 can be seen that in this part of the profile the soil looseness produced by subsoiling is better preserved (penetrability 6 strokes, bulk density 1.54). To what extent a better root development of the oats cover crop assisted in this preservation could not be determined because the oat roots were almost completely disintegrated.

In the plow layer the bulk of the roots are found in the A_{p1} horizon, the depth of secondary tillage such as disking, harrowing, and cultivation. These tillage operations partially recompacted the layer. Area E, A_{p2}, for example, with a bulk density of 1.55 apparently did not provide the optimum tilth for tobacco root development; this

is in contrast with profile areas B and C, A_{p2}, with bulk densities of 1.39 and 1.37, respectively.

Although it is evident that these weakly structured, sandy-textured soils recompact quite easily, the beneficial effect of subsoil shattering in combination with the root activities of cover crops will increase with the years if this practice is repeated on the same fields. Root growth of cover and main crops each year will contribute to the organic matter content and improved physical condition and possibly to the fertility status of the zone below the normal plow layer. After some years these roots probably will impart enough permanence to the loosened subsurface and subsoil layers to reduce the need for further deep tillage operations for 2 or 3 or possibly more years.

This recompaction of the soil caused by tillage operations for the tobacco crop in the spring could obviously be overcome by delaying the subsoiling until just before fitting the land for tobacco. For this purpose an experimental implement has been developed that makes it possible to plow and subsoil with or without deep placement of fertilizer in one operation (9).

Subsoiling with this design fits into the tillage pattern for the Connecticut tobacco crop. Primary tillage for soil preparation is as a rule done in April or May. The subsoiler operates from the bottom of the open plow furrow during plowing, which assures a good lifting action and less compressing and smearing in wet soil (Figure 25). The furrow bottom plus the underlying plow soil and subsoil (A_{p3} and B_{21} horizons) are loosened after the rear tractor wheel has packed it and just before the next plow slice is turned. In this way the compaction pan is shattered at least in the center of every furrow, and its loosened condition is well preserved since directly after it has been shattered, it is covered up by the next furrow slice.

The profile of a treated Merrimac sandy loam plot (Figure 25) does not show any open channels left by the chisel in the B_{21} or B_{22} horizons, as is shown in Figure 20 and 23. The latter plots were treated with the standard chisel-point subsoiler in a separate operation from the land surface.

From the disrupted distinct lower boundary of the A_p horizon, however, one can see where the subsoiler has made its cut and that the grooves are somewhat closer than with the regular subsoiler.

Conditions at the end of the tobacco season are also shown in Figure 26 and Table 2. The fractured and fertilized zones in the compaction pan (A_{p3} + B_{21} horizon) were still open structured (bulk density 1.40) and filled with well branched roots, which penetrated into the deeper subsoil (B_{22} + B_3 horizon). In spite of the narrower spacing of the subsoiler grooves, however, the strips of soil in between these grooves are still compact (bulk density 1.64) and few roots are able to penetrate these areas.

In the A_p horizon the root distribution, however, is very poor, presumably due to recompaction during the secondary tillage operations that prepare the land for tobacco setting. In this case the transplanting machine could very well be the main cause for recompaction of the A_{p2} horizon (bulk density 1.53). The tractor-drawn setter was used when the soil was relatively wet.

The roots in the plow layer (A_{p1+2} horizon) are mainly confined to the upper 2 to 3 inches of soil. Most of the younger roots are adventitious and have grown from the stem base of the plant to spread laterally just below the surface.

The lower boundary of this surface layer (A_{p1} horizon), representing the depth of secondary tillage, was characterized by a very distinct, compacted disk-sole. The few heavy primary roots failed to branch in the uncultivated and repacked part of the plow layer (A_{p2} horizon: penetrability 10½ strokes, bulk density 1.53).

Thus, the root pattern (Figure 26) shows that the opening up of the soil layers, undisturbed by ordinary tillage operations, increased the rooting depth of the tobacco. The bulk of the white succulent younger and absorptive portion of the root system is found in the B horizon of this Merrimac sandy loam profile.

First of all such deepening of the effective rooting zone should considerably improve the water supply of this crop and make it more resistant to drought.

A closer examination of the fertility pattern of the profile, however, shows that especially in drought when few fertilizer salts will be washed into the deeper root zone, this pattern of root growth is highly ineffective as far as the uptake of nutrients is concerned.

According to standard practice all the tobacco fertilizer (3500 pounds of 6-3-6 per acre) was broadcast after fitting the land and worked in by disk-harrowing crossways. After this the land was loosened once more with a spring-tooth harrow just before setting the tobacco seedlings. In this way, this high application of mainly organic fertilizer is well distributed horizontally but is incorporated principally into the top 4 inches of soil or sometimes even less as on the field plot described here.

Tobacco, with a short growing season, requires a good supply of nutrients throughout its life. In cigar leaf production nitrogen exerts a greater influence on yield and quality than any other plant nutrient used. Organic nitrogen fertilizers at the rate of about 1 ton per acre are applied, which break down slowly in the soil and furnish nitrates as plant growth progresses. Nitrogen released from the oil meals is washed by rain into the deeper parts of the root zone.

Under drought conditions, however, the surface layer (A_{p1} horizon) will dry out rapidly and this shallowly placed organic fertilizer will become inactive and furthermore the roots in this layer cannot absorb nutrients from dry soil.

The only efficient method to secure increased yields from a crop with an improved rooting depth, such as shown in Figure 26, may be to place fertilizer near the well branched portion of the root system in the deeper horizons of moist soil.

In the field plot discussed here a deep placement of fertilizer in vertical bands in the fractured zones was applied in conjunction with the subsoiling and plowing operation (9). The subsoil had been tested and was found to be very low in phosphate, as might be expected in Merrimac soils (35). To correct this very low phosphate level and the relatively low potash content of the subsoil layers 360 pounds of triple superphosphate and 126 pounds of KNO_3 per acre were applied.

It is quite evident, however, that this subsoil fertilization should

be considered highly inadequate as the sole source of food for crop growth as soon as the surface layer with the main food supply dries out. Furthermore, it is obvious from the above that many factors are involved in the ultimate effect of deep tillage on crop yields. For a better understanding of the response of various crops to subsoiling a study of the soil-root relationships, as here described, may be helpful.

Gliemeroth (14) made some very interesting investigations concerning the interactions between fertilizer distribution, root development, water and nutrient uptake. Cooke (8) states that in developing fertilizer placement methods for new crops, root systems should be studied. This holds true also for crops with more or less known root growth habits, after the soil and crop management practices have been changed drastically.

Deep Plowing

Very deep plowing as a means of breaking up compacted subsoil layers which impede root development mechanically differs from subsoiling in the following respects. First, if done deep enough it will accomplish a complete destruction of the compaction pan. Second, a more or less complete inversion of the upper soil horizons will be accomplished. As a result the fertility inherent to the A_p horizon will be distributed over the whole depth of deep tillage. Third, good inversion of soil and deep burial of the seeds can be of considerable help in controlling weeds (7).

Deep plowing tests at the Station farm are being conducted on well-drained Windsor loamy sand with a definite compaction pan at a depth of 8 to 9 inches.

The first year the field plots were plowed 11 inches deep in late summer following the tobacco harvest. The second fall the same areas were again deep plowed, this time to a depth of 14 inches. On most plots this 14-inch plowing depth almost completely disrupted the compaction pan.

Both years the deep plowed land was directly disk-harrowed and sowed with various cover crops. The following spring the land was plowed again, but now as shallow as possible, so-called skim plowed. In this way the tops of the cover crops, which were not winter-killed, were worked into the soil just far enough to fit the land for the tobacco setting.

Soil-root relationship investigations again were made to study the effect of these soil management practices on soil properties and the root growth of the tobacco. In these experiments Broadleaf tobacco was used as test crop.

The root studies on two of these plots which were plowed 14 inches deep, are presented in Table 3 and Figures 27 and 28. In one case (Figure 27) the deep plowed plot grew a luxurious cover crop, a mixture of oats and rye, that was turned under only 6-7 inches in the second half of May. In the other case (Figure 28), the rape cover crop was a total failure and these plots, also shallow spring plowed, are designated "no cover crop."

Although in both cases tobacco roots developed abundantly at greater depths due to the complete destruction of the compaction pan

Table 3. Description of profiles and root distribution shown in Figures 27 and 28

Depth beneath hill	Plow zone and horizon	Root weight: Oven dry	Root weight: Relative below 6″	Sampling depth[1]	Plow zone	Bulk density	Field moisture	Penetrability
Inches		g/100	Per cent	Inches		g/cc	Per cent	No. of strokes
				Cover crop, oats and rye				
0 to 6½	A_{ps}[2]	4528	...	2 to 4	A_{p1}	1.32	8.8	4¼
6½ to 12	A_{pf}[3]	325	48.7	8 to 10	A_{pf} (upper)	1.45	9.8	9¼
12 to 20	A_{pf} & B_3	342	51.3	13 to 15	A_{pf} (lower)	1.41	9.5	6½
				No cover crop				
0 to 8½	A_{p1} & A_{ps}	5138 + 90	16.5	2 to 4	A_{p1}	1.33	8.4	4¼
8½ to 12	A_{pf}	82	15.1	9 to 11	A_{pf} (upper)	1.52	8.5	13¼
12 to 20	A_{pf} & B_3	372	68.4	13 to 15	A_{pf} (lower)	1.45	9.2	7¼

[1]Average of six determinations. See Figures for locations.
[2]Zone of spring plowing, 6 to 7 inches deep.
[3]Zone of fall plowing alone, 14 inches deep.

by deep plowing, a marked difference in root distribution throughout the upper portion of the fall plowed zone (A_{pf}) and the lower part of the spring plowed zone (A_{ps}) was produced by the cover crop. Where there had been a cover crop (Figure 27) a rather uniformly distributed dense network of roots exists throughout the zone of spring plowing (A_{ps}). The lower boundary of this zone is noticeable in root development, but it is not distinct and abrupt. On the other hand in the absence of a cover crop (Figure 28) most roots in the A_{ps} zone are abruptly confined to the depth of secondary tillage (A_{p1}).

The way in which the cover crop produced increased root growth is indicated by the soil's physical properties. (Table 3). Where there was a cover crop the 6½- to 12-inch zone remained less dense (bulk density 1.45). On the other hand, where there was no cover crop, the soil became compact (bulk density 1.52) and hard (penetrability 13¼ strokes) in the comparable zone, 8½ to 12 inches here.

Evidently due to the growth of the winter cover crop on the plot of Figure 27 the open structure established by the fall deep plowing was better preserved or offered more resistance to compaction during spring tillage. The secondary tillage operations on the spring-plowed land, especially, were probably better cushioned by the turned-under top growth of the rye cover crop.

With or without cover crop, the root concentration of the tobacco in the lower part of the deep plowed zone (bulk density 1.41 to 1.45) and the adjacent deeper subsoil is quite dense.

Problem of Soil Recompaction

It is evident from the studies presented here that one of the biggest problems in improving the effective rooting depth of tobacco is the problem of how to prevent recompaction in these weakly structured sandy soils after they have been either loosened or fluffed up by subsoiling, shallow, normal, or deep plowing. This problem is becoming more and more common as heavier tractors and farm implements are being used more frequently. We recognize that sandy-textured soils are easy to work, but we seldom realize that these soils may be readily compacted.

Compaction pans at plow depth, so-called plowsole hardpans, are easily recognized (Figures 2, 3, 4, and 5). They result from plowing at the same depth year after year and thus building up a compaction zone by the compression action of the plow share and machinery traffic on the moist soil in the furrow bottom. Such induced pans usually occur at a depth of 8 to 16 inches.

The compaction induced by secondary tillage, i.e. fitting and cultivating the plowed land, is harder to recognize. Studies of the soil-root relationships, however, are indicative of the suitability of the root environment for that particular plant.

The root studies clearly indicate that the disk-harrow, an implement much used to fit the land and to incorporate the fertilizer, creates a distinct disk-sole in moist soil, often dense enough to retard tobacco root growth (Figures 5, 23, 24, 26, 28, and 29, p. 30). The threshold densities above which tobacco roots do not penetrate and ramify in these moderately coarse-textured soils seem to be in the

range 1.52 to 1.54 depending on the hardness of the soil as measured by resistance to sampler penetration.

It is obvious that tractors and implements should go on the plowed land as little as possible to minimize compaction of the soil just below the surface. Excessive stirring and pulverization of the weakly structured soils should be avoided. The tilth of the root bed for the tobacco seedlings should not be made too fine or it may collapse into a compact layer if wet weather follows.

Lighter weight tractors are known to have definite advantages over heavy ones for cultivation purposes (34). In view of the fact that excessive cultivation appears to be detrimental, some supplement to cultivation seems to be desirable. A chemical weed killer or a mulch could certainly be used to advantage.

A comparison of Figures 29 and 30 brings out very strikingly the benefit of eliminating as much tractor and implement traffic as possible. Figure 29 represents an extreme case of root bed deterioration from conventional mechanized tillage operations. Figure 30, on the other hand, shows root growth of tobacco grown in the same field and at the same time in a deep open-structured profile. This plot was first loosened with a fork and then planting and all further tillage was done by hand with as little soil packing as possible. Otherwise, the treatments on both plots were identical.

Evidently the use of heavy farm machinery will have to be considered very carefully, in order to avoid destruction of the open tilth set up by plowing or deep tillage, particularly with soils which are easily compacted.

In addition to proper attention to reducing and to better timing of operations with respect to the moisture status of the soil, the incorporation of considerable amounts of organic matter should also help prevent the development of compaction zones.

Annual cover crops which act as green manure should be planted not only to provide soil cover but also to improve soil structure and preserve tilth. These crops should be selected for their ability to provide bulk or for their root system (16), which should preferably be fibrous and ligneous and able to penetrate compact subsoils (Figure 16, and page 26).

The main function of tops and root crowns, when turned under by spring plowing, is to exert a cushion effect that will resist the compressive action of implements and traffic and particularly prevent the forming of a sharply defined stratum, such as a disk sole, within the plow layer (Figure 27, and page 33).

If kept near the surface these non-humified plant residues will not only prevent a complete breakdown of the tilth of the soil in the lower part of the plow zone (A_{p2} horizon), but will also stabilize the surface tilth and minimize the tendency of these sandy, weakly structured soils to form unfavorable surface crusts under rain. A sealed soil surface will cause poor soil aeration for a few days after each heavy rain. Soils containing a high proportion of fine sand or very fine sand, such as many Connecticut tobacco soils, are particularly susceptible to surface crusting.

The deeper root growth of these cover and green manure crops should help maintain or improve the tilth of the subsurface or subsoil horizons,

either with or without the help of deep tillage for deeper penetration (Figures 18 and 21, and page 29).

Application of fertilizers to the cover-crops, either as deep placement or as top dressing, for more vigorous growth, should also be helpful. The fertilizers applied are largely available to succeeding crops when the green manure has decomposed.

It is obvious that the problem of securing optimum root development is closely linked with soil management. There appears to be no question that deep tillage plus reducing of machine traffic and secondary tillage, and introduction of green manure crops will overcome most of the traffic and tillage pans.

The tobacco growers in Connecticut are in a favorable position to do something about this problem, because the tobacco is on the land but about 2½ months. During the rest of the year good use can be made of the structure-forming effects of the strongly branched fibrous root systems of annual cover on green manure crops.

Literature

1. Albrecht, D., Fritzsche, K.H., and Winkler, G. Weitere Entwicklung des Strukturbohrers. D.Dtsch.Landwirtschaft 4. 1953.
2. Anderson, P.J. Growing tobacco in Connecticut. Conn.Agr.Expt.Sta.Bul.564. 1953.
3. Anma, M. and Oda, K. A new method of root system study in field experiment. Jour.Kanto-Tosan Agr.Expt.Sta.No.4:1-10. 1953.
4. Bourbeau, G.A., and Swanson, C.L.W. The morphology, mineralogy and genesis of two southern New England soils. Conn.Agr.Expt.Sta.Bul.584. 1954.
5. Broadfoot, W.M. Procedures and equipment for determining soil bulk density. Southern Forest Exp.Sta.Occ.Pap.135:2-11. 1954.
6. Carlson, C.A. A core method for determining the amount and extent of small roots. Southern Forest Exp.Sta.Occ.Pap.135:43-47. 1954.
7. Chepil, W.S. Germination of weed seeds; the influence of tillage treatment on germination. Sci.Agr.26:347-357. 1946.
8. Cooke, G.W. Recent advances in fertilizer placement. Jour.Sci.Food Agric. 5,9: 429-440. 1954.
9. de Roo, H.C. Subsoiling, plowing and deep placement of lime or fertilizer in one operation. Agron.Jour.48:476-477. 1956.
10. Fehrenbacher, J.B., and Alexander, J.D. A method for studying corn root distribution using a soil-core sampling machine and shaker-type washer. Agron.Jour. 47 (10):468-472. 1955.
11. Fox, R.L., and Lipps, R.C. Influence of soil-profile characteristics upon the distribution of roots and nodules of alfalfa and sweetclover. Agron.Jour.47 (8): 361-367. 1955.
12. Fribourg, H.A. A rapid method for washing roots. Agron.Jour.45 (7):334-335. 1953.
13. Gier, L.J. Root systems of Bright Belt Tobacco. Am.Jour.Bot.27 (9):780-787. 1940.
14. Gliemeroth, G. Bearbeitung und Düngung des Unterbodens in ihrer Wirkung auf Wuzelentwicklung, Stoffaufnahme und Pflanzenleistung. Zschr.f.Acker- und Pflanzenbau 96:1-44. 1953.
15. Goedewaagen, M.A.J. De methoden, die aan het Landbouwproefstation en Bodemkundig Instituut T.N.O. te Groningen bij het wortelonderzoek op bouw- en grasland in gebruik zijn. Landbouwproefstation Groningen, Netherlands. 1948.
16. Goedewaagen, M.A.J., and Schuurman, J.J. Root production by arable and grass crops. Trans.4th Int.Congr.Soil Sci. (Amsterdam) 1950,2,28-31.
17. Gold, T.S. Fifth Annual Report Connecticut Board of Agriculture, 1871. Hartford, 1872.
18. Görbing, J. Die Grundlagen der Gare im praktischen Ackerbau. Hannover, Landbuch-Verlag. 1947.
19. Johnson, S.W. Soil exhaustion and rotation of crops. Fifth Annual Report Connecticut Board of Agriculture: 75-99. 1871-72.

20. Köhnlein, J., and Vetter, H. Ernterückstände und Wurzelbild. Verlag Paul Parey, Berlin u. Hamburg 1953.
21. Kramer, P.J. and Jackson, T.J. Causes of injury to flooded tobacco plants. Plant Physiol. 29:241-245. 1954.
22. Lunt. H.A., Swanson, C.L.W., and Jacobson, H.G.M. The Morgan soil testing system. Conn.Agr.Expt.Sta.Bul.541. 1950.
23. Maschhaupt, J.G. Root systems of agricultural plants. Versl. Landbouwk.Onderz. 16, 76-89. 1915.
24. Morgan, M.F. The soil characteristics of Connecticut land types. Conn.Agr.Expt. Sta.Bul.423. 1939.
25. Pavlychenko, T.K. The soil-block washing method in quantitative root study. Canadian Jour.Res., 15:33-57. 1937.
26. Raney, W.A. Field measurement of oxygen diffusion through soil. Soil Sci.Soc. Amer.Proc., 14:61-65, 1950.
27. Schuurman, J.J., and Goedewaagen, M.A.J. A new method for the simultaneous preservation of profiles and root systems. Plant and Soil 6 (4): 373-381. 1955.
28. Sekera, F. Gesunder und Kranker Boden. Paul Parey, Berlin, 3 Aufl. 1951.
29. Simon, W., and Eich, D. Probleme und Methoden der Wurzeluntersuchungen. Z.Acker- u. Pfl.Bau 100: 179-198. 1955.
30. Soil Survey Staff. B.P.I.S. and A.E. Soil Survey manual. U.S.D.A. Handbook No.18, U.S.Government Printing Office, Washington, D.C. 1951.
31. Swanson, C.L.W. A portable soil core sampler and penetrometer. Agron.Jour. 42:447-451. 1950.
32. Swanson, C.L.W., Shearin, A.E., and Bourbeau, G.A. Characteristics of some brown podzolic profiles in the central lowland of Connecticut and Massachusetts. Soil Sci.Soc.Amer.Proc. 16:203-207. 1952.
33. Swanson, C.L.W., and Ritchie, A.,Jr. Significance of sand and gravel in the classification, mapping and management of some coarse-textured soils. Conn. Agr.Expt.Sta.Bul. 580. 1954.
34. Swanson, C.L.W. Some physical facts about Connecticut soils. Jour.Soil&Water Conserv., May, 1954.
35. Tamura, T. Physical, chemical, and mineralogical properties of brown podzolic soils in Southern New England: Paxton and Merrimac series. Soil Sci. 81:287-299. 1956.
36. Tollenaar, D. Onderzoekingen over de ontwikkeling van het wortelstelsel van tabak onder verschillende omstandigheden. Proefstation voor Vorstenlandse Tabak, Mededeeling 65:1-47. 1930. English summary.
37. Upchurch, R.P. The use of the trench-wash and soil-elution methods for studying alfalfa roots. Agron.Jour. 43:552-555. 1951.
38. Upchurch, R.P., and Lovvorn, R.L. Gross morphological root habits of alfalfa in North Carolina. Agron.Jour.43:493-498. 1951.
39. Visser, W.C., and Goedewaagen, M.A.J. Een onderzoek naar bodemstructuur en wortelontwikkeling. Landbouw.Tijdschrift 55:405-432. 1943.
40. Ward, H.S.,Jr. Reactions of adapted legumes and grasses on the structural condition of eroded Lindley-Weller soils in southeastern Iowa. Ecol.Monog. 19 (2):145-171. 1949.
41. Weaver, J.E. Root development of field crops. McGraw-Hill Book Co.,Inc. New York. 1926.
42. Weaver, J.E. The ecological relations of roots. Carnegie Inst. Wash., Pub.286: 2-3. 1919.
43. Weaver, J.E., and Darland, R.W. Soil-root relationships of certain native grasses in various soil types. Ecol.Monog. 19: 303-338. 1949.